Impact of Sterile Neutrino in Long Baseline Experiments

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This talk is based on arXiv: 1601.05995 & 1603.03759

Outline

Part I : Based on arXiv: 1601.05995 by S. K. Agarwalla, S. S. Chatterjee, A. Dasgupta & A. Palazzo

- **Introduction (The SBL Anomalies & light sterile neutrinos)**
- **Impact of sterile neutrino in T2K & NOvA**

Part II : Based on arXiv: 1603.03759 by S. K. Agarwalla, S. S. Chatterjee & A. Palazzo

- **Physics reach of DUNE with a sterile neutrino**

Part III : Conclusion

Gallium Anomaly

Two Gallium Experiments : GALLEX & SAGE

ν_e sources : $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$

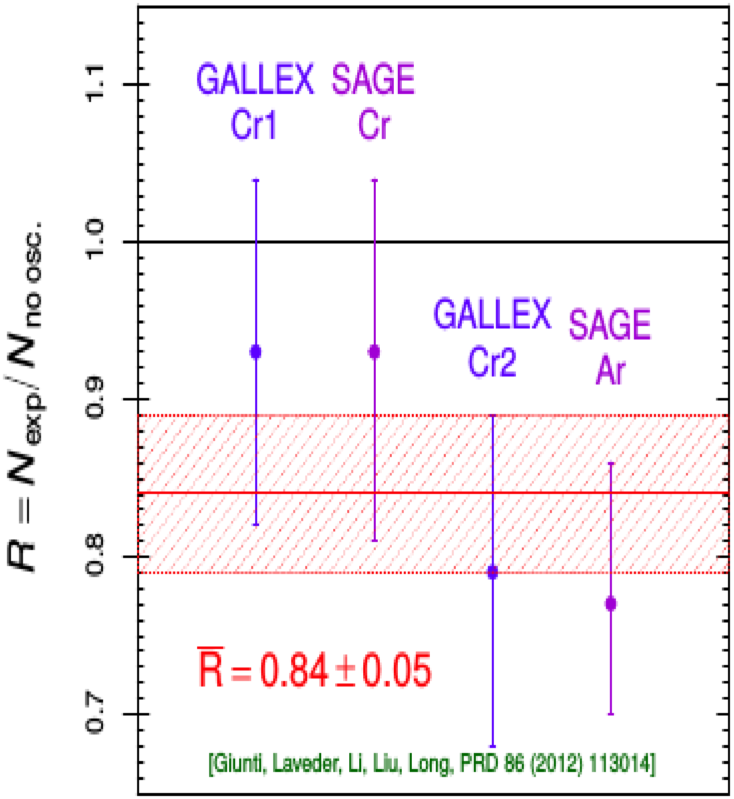
$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$

Detection process : $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

$\nu_e \to \nu_e$ Oscillation

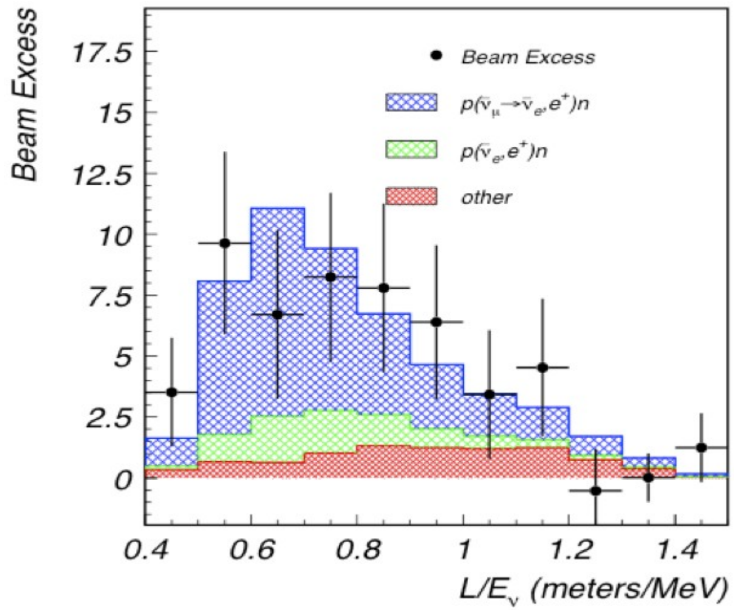
$L \simeq 1\,m$, $E \simeq 1$ MeV, 2.9σ deficit

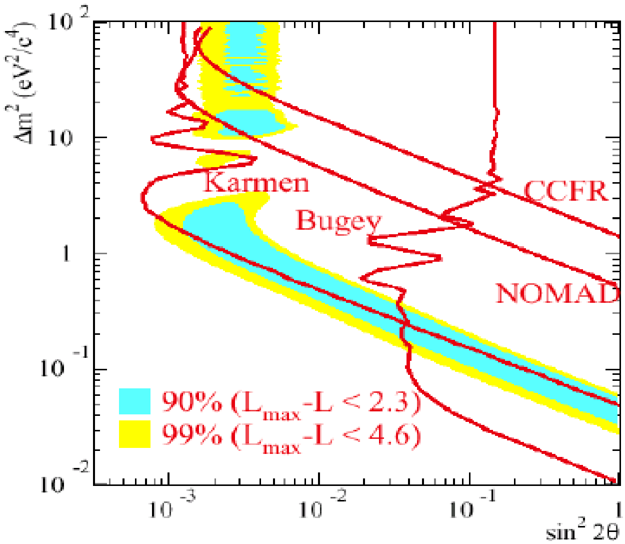
To explain it, one possibility may be $\Delta m^2 \approx 1\ eV^2$



SAGE PRC 73(2006) 045805; PRC 80 (2009) 015807
Laveder et al. Nucl. Phys. Proc. Suppl. 168 (2007) 344; MPLA 22 (2007) 2499;
PRD 78 (2008) 073009; PRC 83 (2011) 065504; PRD 86 (2012) 113014

LSND Anomaly





$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation

$L \simeq 30\ m,\ \ 20\ MeV \leqslant E \leqslant 60\ MeV$

Source : $\mu^+(\text{rest}) \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Detection process : $\bar{\nu}_e + P \rightarrow n + e^+$

LSND observed an excess 3.9σ $\bar{\nu}_e$ events in $\bar{\nu}_\mu$ beam

The signal can be explained if $\Delta m^2 \gtrsim 0.1\ eV^2$

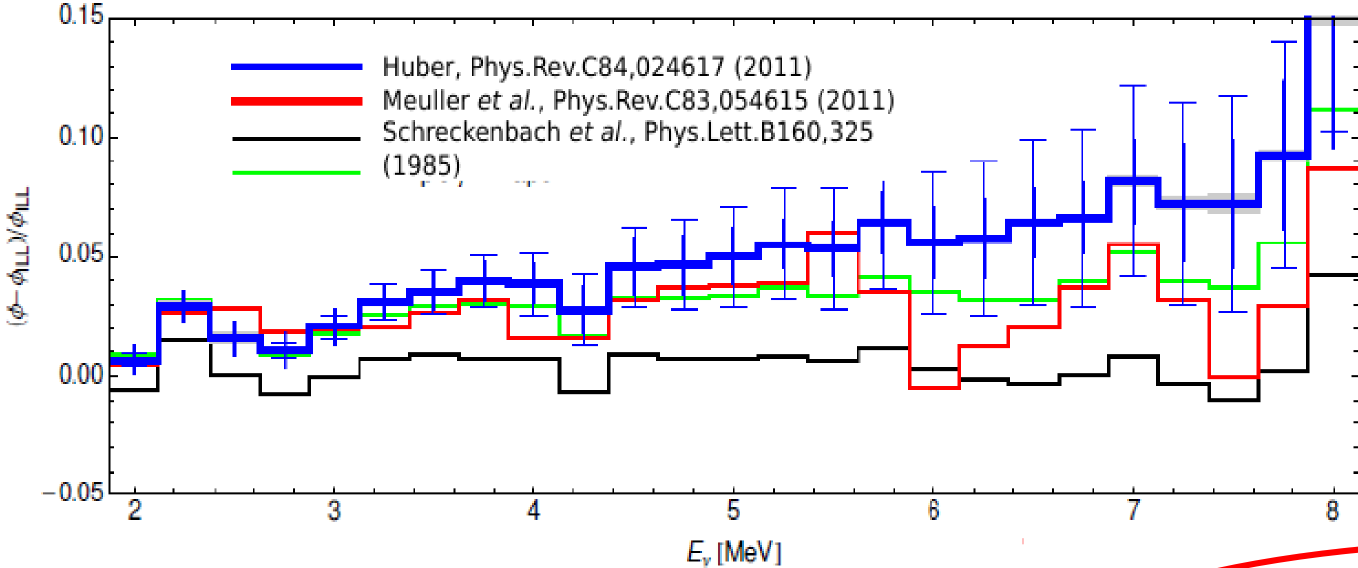
The Karmen ($L \sim 18$ m) Collaboration did not see the same but could not exclude it fully.

A.Aguilar-Arevalo et al. [LSND Collb.], PRD 64 (2001) 112007

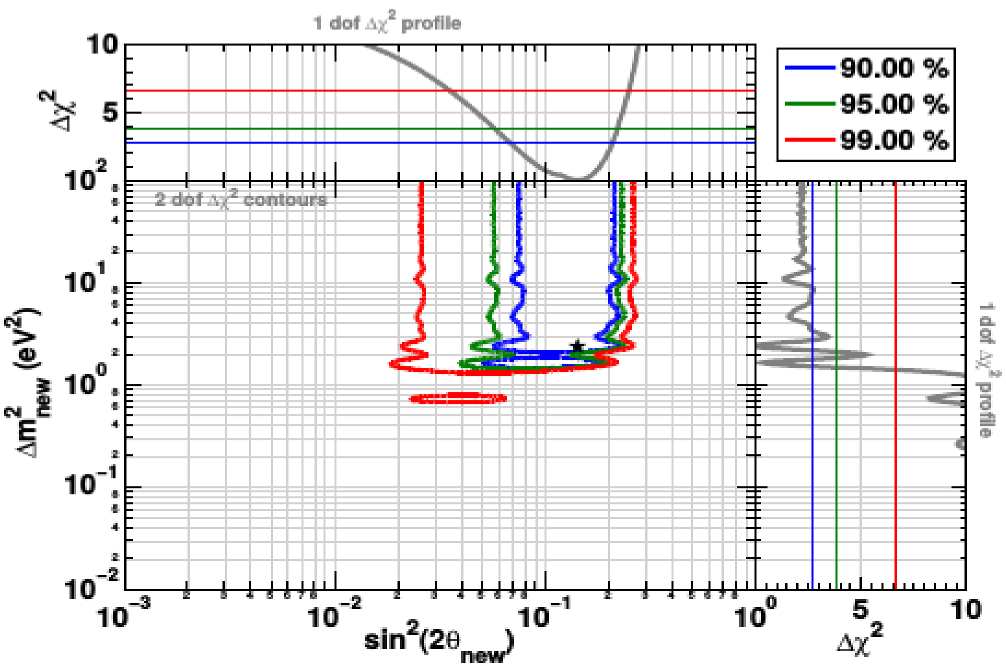
B.Armbruster et al. [KARMEN Collb.], PRD 65 (2002) 112001

Reactor Anomaly

New analyses (blue and red) of the reactor $\bar{\nu}e$ spectrum predict a 3% higher flux than the existing calculation (black).



There is almost 7% discrepancy between observed to expected event rates



Require eV scale sterile neutrino to explain the anomaly

See ''The reactor antineutrino anomaly'' by G Mention [J. Phys. :Conf. Ser. 408 (2013) 012025]

Experiments to Search for Sterile Neutrinos

There are four types of experiments broadly categorized as:

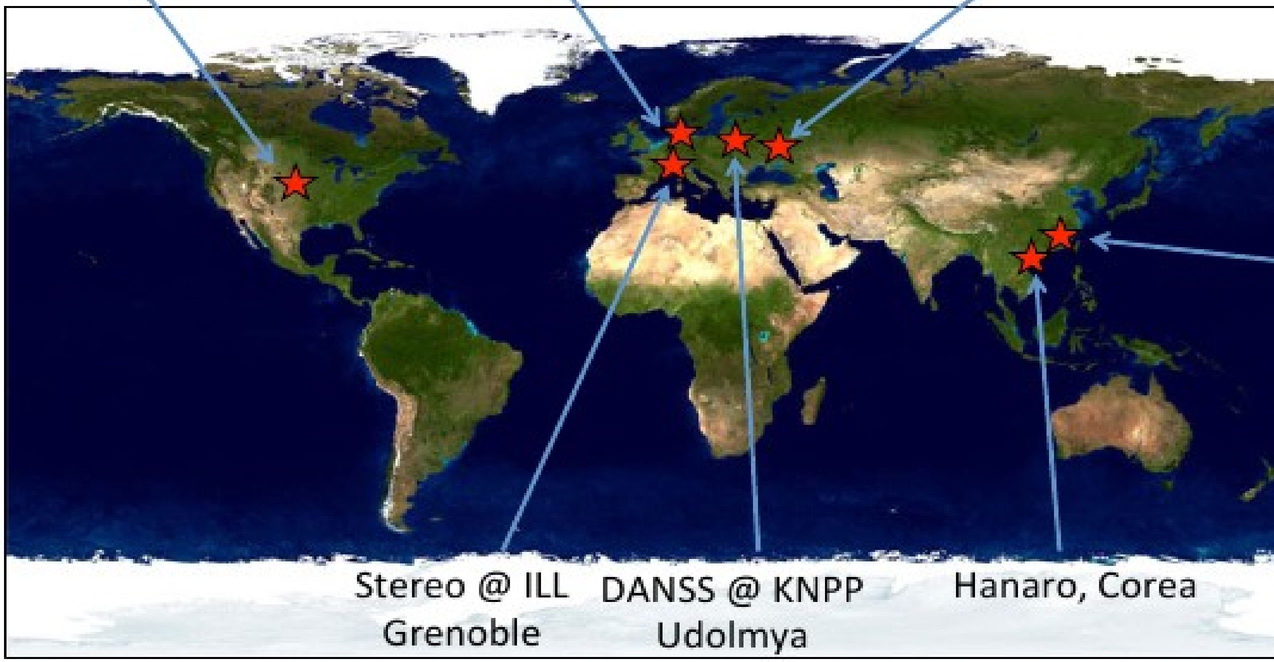
Radioactive Neutrino Sources: SOX, LENS, Baksan, Ce-LAND, RICOCHET …….

Reactor Neutrinos: Stereo, DANNS, US SBR, Neutrino-4, SoLid, Nucifier …..

Stopped π beams : OscSNS, LSND-Reloaded, IsoDAR …..

Decay in Flight Beams : nuSTORM, LAr1, ICARUS / NESSiE ….

For details please see the talk by Jonathan Link, Virginia Tech.



See the talk by D.Lhuillier - CEA Saclay

Theoretical Framework

In presence of a sterile neutrino ν_s , the 4x4 mixing matrix between flavor & mass eigenstates is parametrized as :

$$U = \tilde{R}_{34} R_{24} \tilde{R}_{14} R_{23} \tilde{R}_{13} R_{12} \longrightarrow 3\nu$$

where, R_{ij} & $\tilde{R}_{ij}$ *are* real (complex) 4×4 rotations in the (i, j) plane containing the 2×2 submatrix

$$R_{ij}^{2\times 2} = \begin{pmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{pmatrix}$$ and $$\tilde{R}_{ij}^{2\times 2} = \begin{pmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}^{*}_{ij} & c_{ij} \end{pmatrix}$$

3ν → Mixing angles (3)

3ν → Phases (Dirac + Majorana) (1 + 2)

4ν → Mixing angles (6)

4ν → Phases (Dirac + Majorana) (3 + 3)

The choice of this parametrization is completely convenience. Such as

(i) When mixing involving fourth state is zero (i.e, $\theta_{14} = \theta_{24} = \theta_{34} = 0$), it returns to the 3-flavor mixing matrix.

(ii) With the left most positioning of the matrix $\tilde{R}_{34}$ the vacuum transition probability $\nu_\mu \rightarrow \nu_e$ becomes independent of θ_{34} & δ_{34} [See Klop & Palazzo; PRD 91 (2015) 073017]

(iii) For small values of θ_{13} & mixing angles involving 4th state, we have, $|U_{e3}^2| \simeq s_{13}^2$, $|U_{e4}^2| \simeq s_{14}^2$, $|U_{\mu 4}^2| \simeq s_{24}^2$, and $|U_{\tau 4}^2| \simeq s_{34}^2$

with an immediate physical interpretation of mixing angles.

Appearance Probability ($P^{4\nu}_{\mu e}$) in Vacuum

We consider $\Delta m^2_{41} \sim 1 eV^2$ light sterile neutrino

$\Delta m^2_{41} \gg \Delta m^2_{31}$ $\longrightarrow$ Fast oscillations get averaged out

No phase information related to Δm^2_{41} in contrast to SBL

But LBL setups are sensitive to CP phases in contrast to SBL

$$P^{4\nu}_{\mu e} \simeq P^{\rm ATM} + P^{\rm INT}_{I} + P^{\rm INT}_{II}$$

$$s_{13} \sim s_{14} \sim s_{24} \sim \varepsilon$$

$$P^{\rm ATM} \simeq 4 s^2_{13} s^2_{23} \sin^2\Delta \qquad \sim O(\varepsilon^2)$$

$$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31} \sim \varepsilon^2$$

$$P^{\rm INT}_{I} \simeq 8 s_{12} c_{12} s_{13} s_{23} c_{23} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) \qquad \sim O(\varepsilon^3)$$

$$\Delta \equiv \Delta m^2_{31} L / 4E$$

$$P^{\rm INT}_{II} \simeq 4 s_{13} s_{23} s_{14} s_{24} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) \qquad \sim O(\varepsilon^3)$$

See Klop & Palazzo; PRD 91 (2015) 073017

Independent of δ_{34} & θ_{34} in vacuum

Matter Effect

In presence of matter, the leading term in transition probability $P(\nu_\mu \to \nu_e)$ modified as (upto third order)

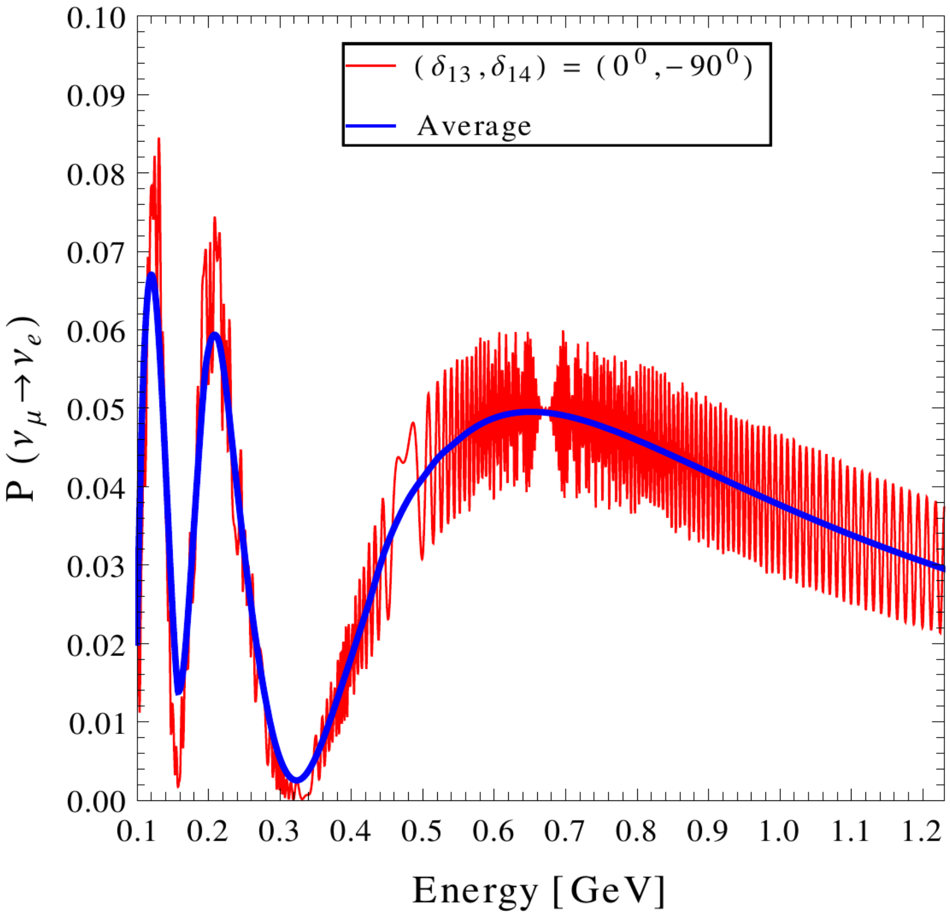
$$P_m^{ATM} \simeq (1+2k) P^{ATM}$$

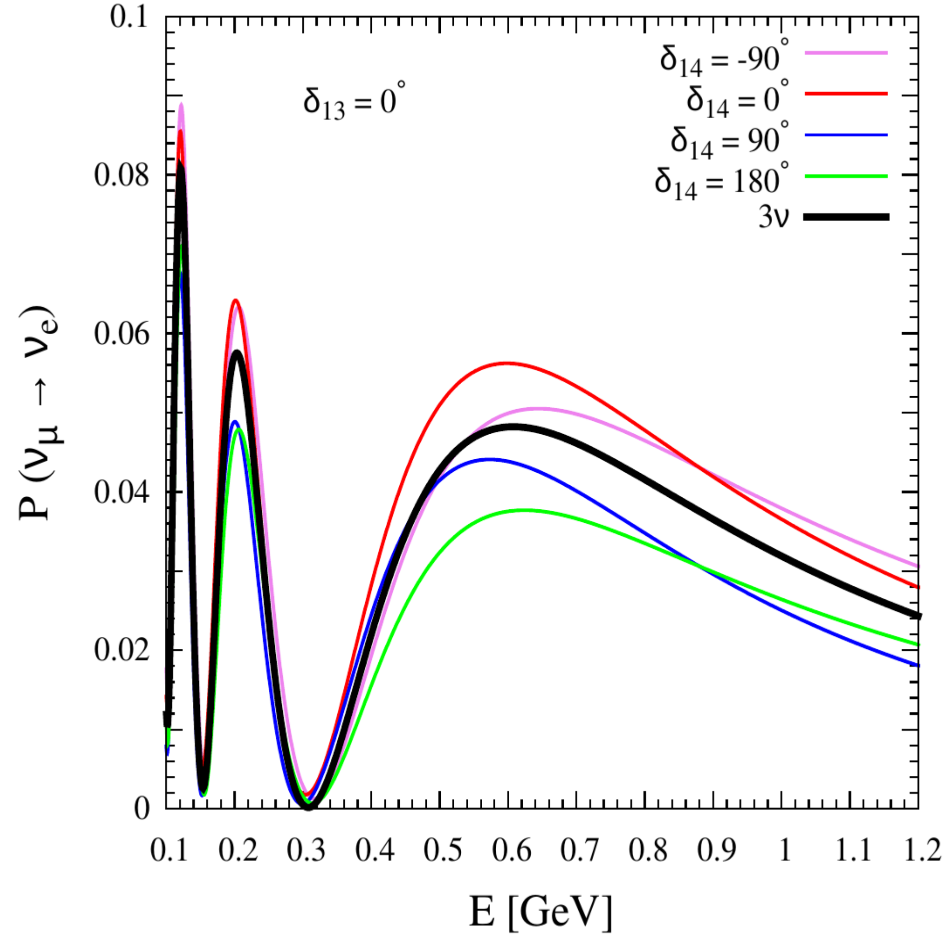
$$k = \frac{2VE}{\Delta m_{31}^2} \quad \& \quad V = \sqrt{2} G_F N_e$$

It can be shown that the two interfernce terms acquire Corrections which are of the fourth order. In this work we limit ourselves upto third order i.e., ε^3. So the interference terms will have the vacuum expressions.

θ_{34} & δ_{34} dont come into the picture

Though the oscillation driven by Δm^2_{41} gets averaged out, it has huge effect at far detector





3-flavor case :

$$P = P_0 + A\left(\cos\Delta\,\cos\delta_{13} - \sin\Delta\,\sin\delta_{13}\right)$$

$$\bar{P} = \bar{P}_0 + \bar{A}\left(\cos\Delta\,\cos\delta_{13} + \sin\Delta\,\sin\delta_{13}\right)$$

$$A = \bar{A} \simeq 8\, s_{12} c_{12} s_{13} s_{23} c_{23} (\alpha\Delta) \sin\Delta$$

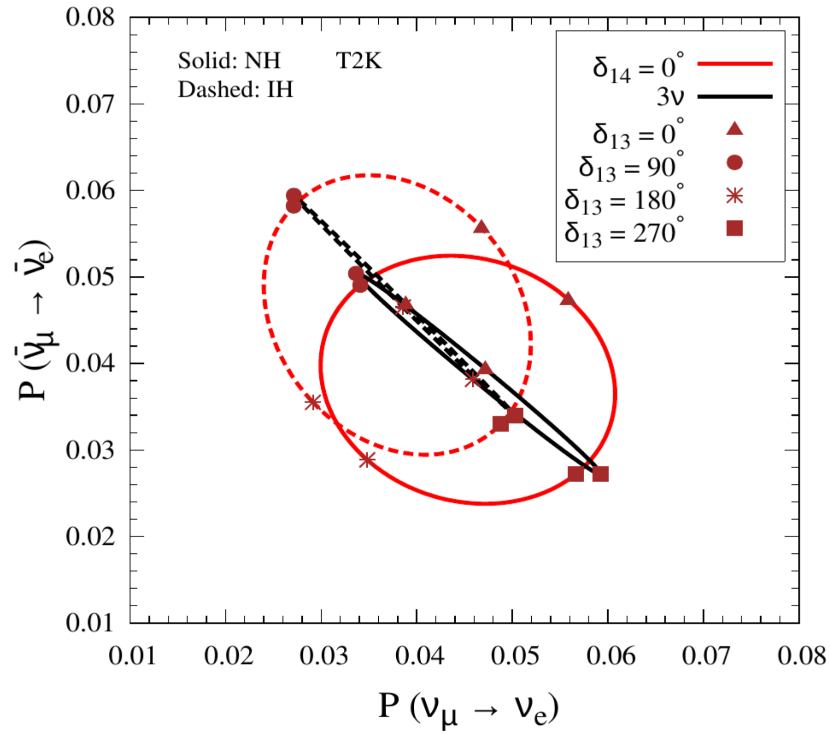
After a counter clockwise rotation by an angle ω one can obtain,

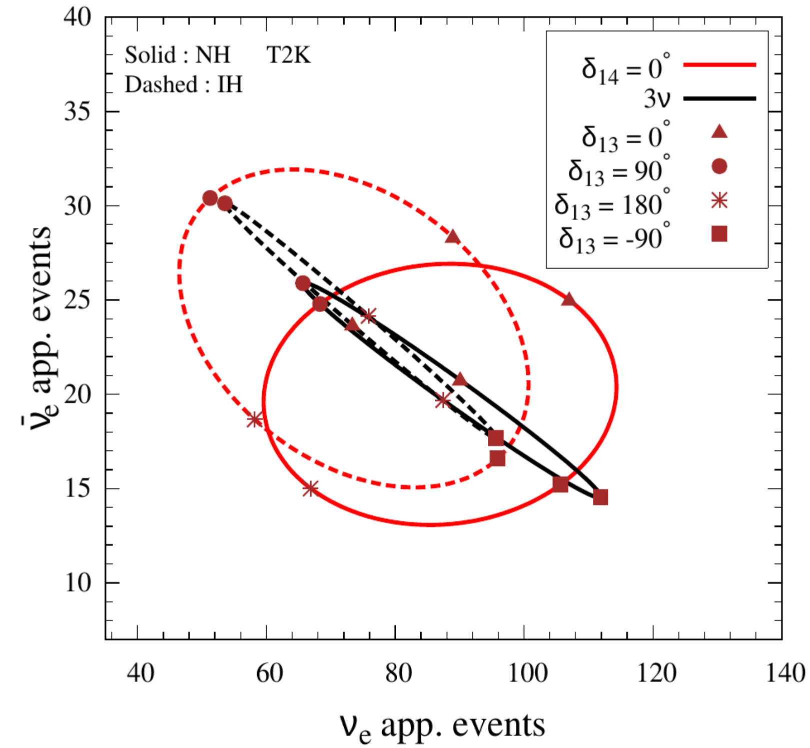
$$\frac{(\bar{P}' - P_o)^2}{a^2} + \frac{(\bar{P}' - P_o)^2}{b^2} = 1$$

$$a = \sqrt{2}\ A\ \sin\Delta$$

$$b = \sqrt{2}\ A\ \cos\Delta$$

For 4-flavor case,
please see arXiv: 1601.05995





Parameter	True Value	Marginalization Range
$\sin^2\theta_{12}$	0.304	Not marginalized
$\sin^2 2\theta_{13}$	0.085	Not marginalized
$\sin^2\theta_{23}$	0.50	[0.34, 0.68]
$\sin^2\theta_{14}$	0.025	Not marginalized
$\sin^2\theta_{24}$	0.025	Not marginalized
$\sin^2\theta_{34}$	0, 0.025, 0.25	Not marginalized
$\delta_{13}/^\circ$	[- 180, 180]	[- 180, 180]
$\delta_{14}/^\circ$	[- 180, 180]	[- 180, 180]
$\delta_{34}/^\circ$	[- 180, 180]	[- 180, 180]
$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2}$	7.50	Not marginalized
$\frac{\lvert\Delta m^2_{32}\rvert}{10^{-3}\,\mathrm{eV}^2}$	2.4	Not marginalized
$\frac{\Delta m^2_{31}}{10^{-3}\,\mathrm{eV}^2}$ (NH)	(2.4 + 0.075)	Not marginalized
$\frac{\Delta m^2_{31}}{10^{-3}\,\mathrm{eV}^2}$ (IH)	- 2.4	Not marginalized
$\frac{\Delta m^2_{41}}{\mathrm{eV}^2}$	1.0	Not marginalized

arXiv : 1601.07777 by F. Capozzi, E. Lisi, A. Marrone, D. Montanino & A. Palazzo

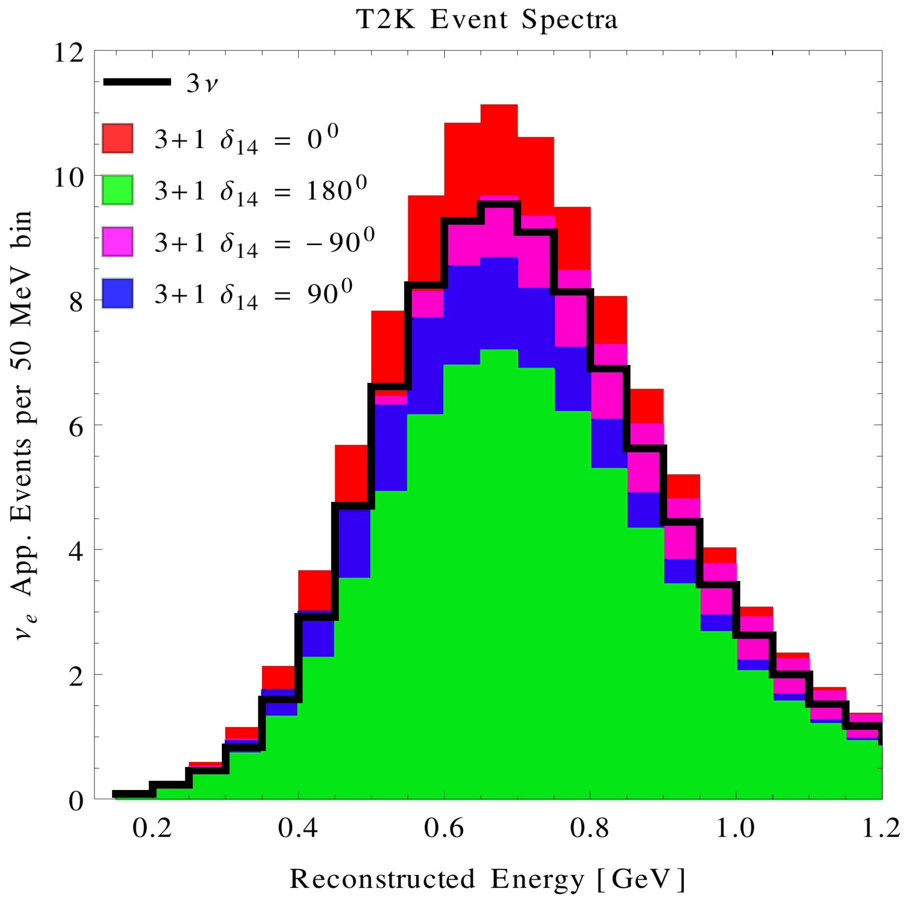
arXiv : 1405.7540 by D. V. Forero, M. Tortola & J. W. F. Valle

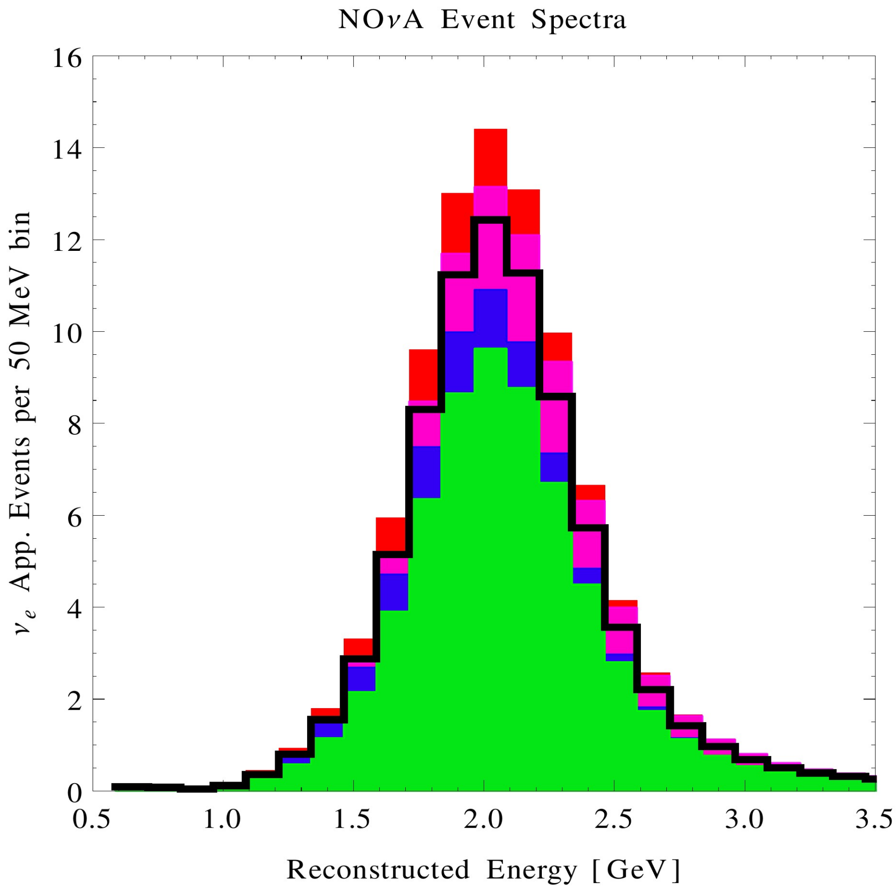
arXiv : 1409.5439 by Gonzalez-Garcia, Maltoni & Schwetz

arXiv : 1303.3011 by Kopp, Machado, Maltoni & Schwetz

Experimental Set-up & Event Spectra of T2K and NOvA

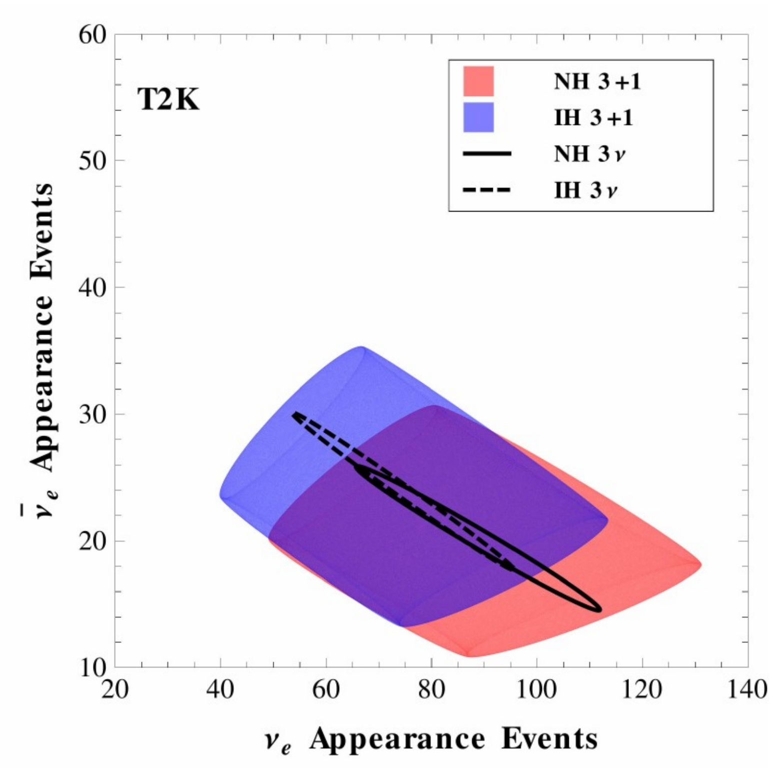
T2K ~ 295 km & NovA ~ 810 km baseline

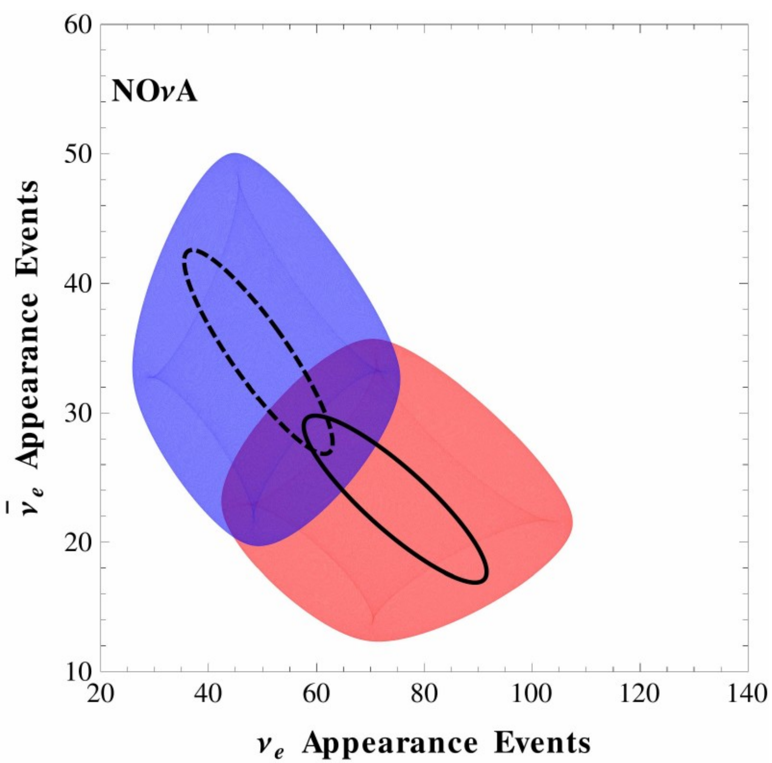




Events are peaked almost at their oscillation maxima due to the off-axis nature of both the experiments

Bi-events covoluted plots

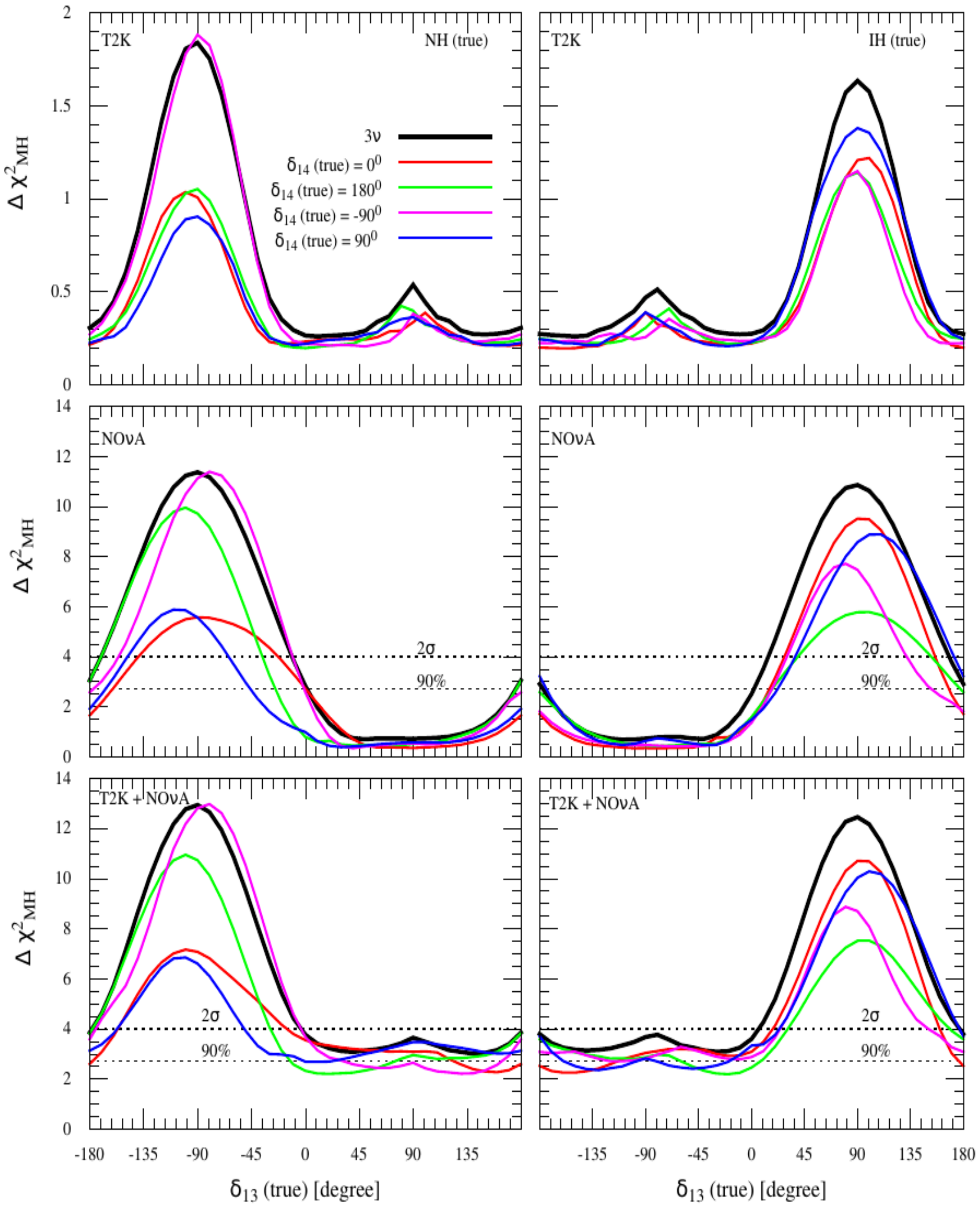


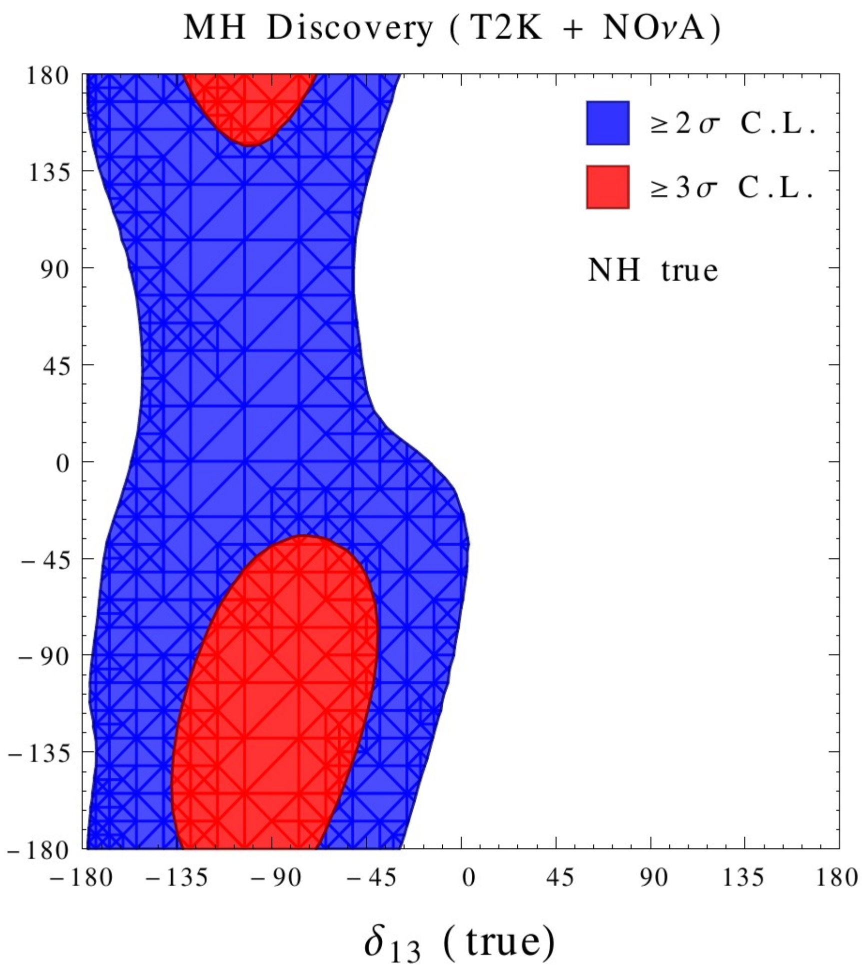


Color Blobs are obtained by superimposing several ellipses corresponding to different combinations of δ_{13} & δ_{14}

T2K is almost insensitive to MH but for certain favorable combination of phases, NovA can tell some information about MH

Mass Hierarchy Determination



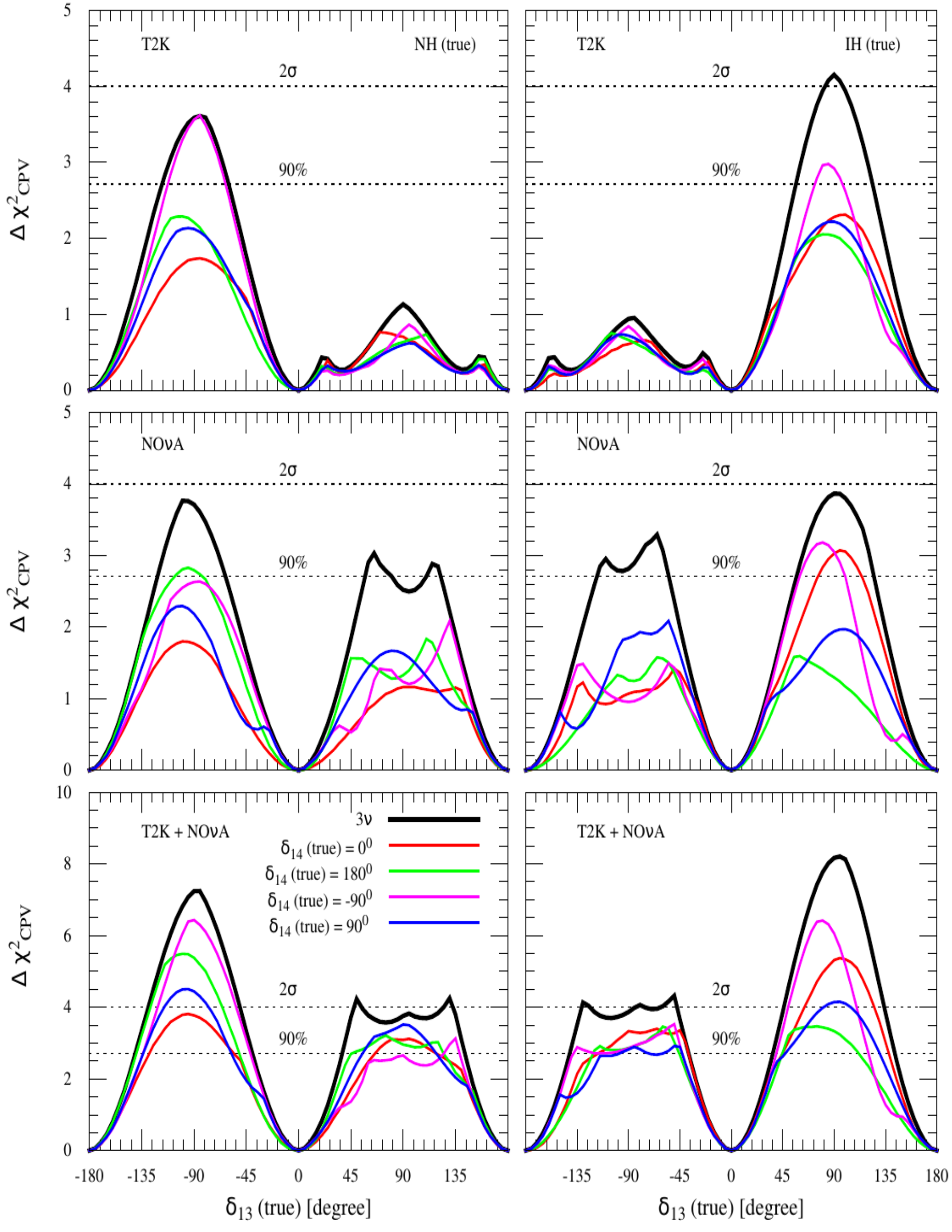


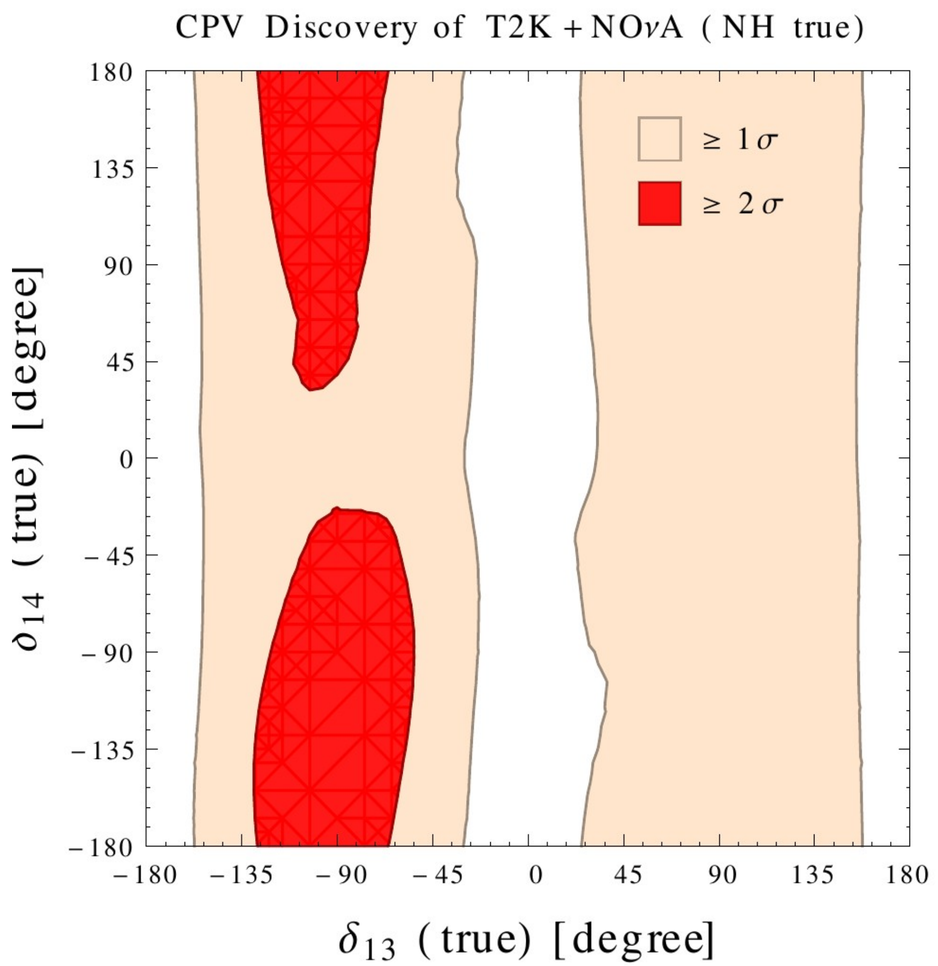
- In the determination of MH, NOvA always dominates over T2K due to it's large matter effect

- Combining both T2K & NOvA are complimentary to each other in the determination of MH though T2K does not help much

- MH gets substantially deteriorated w.r.t SM expectation depending upon the phase value of δ_{14}

CP-violation Searches in Presence of a Sterile Neutrino



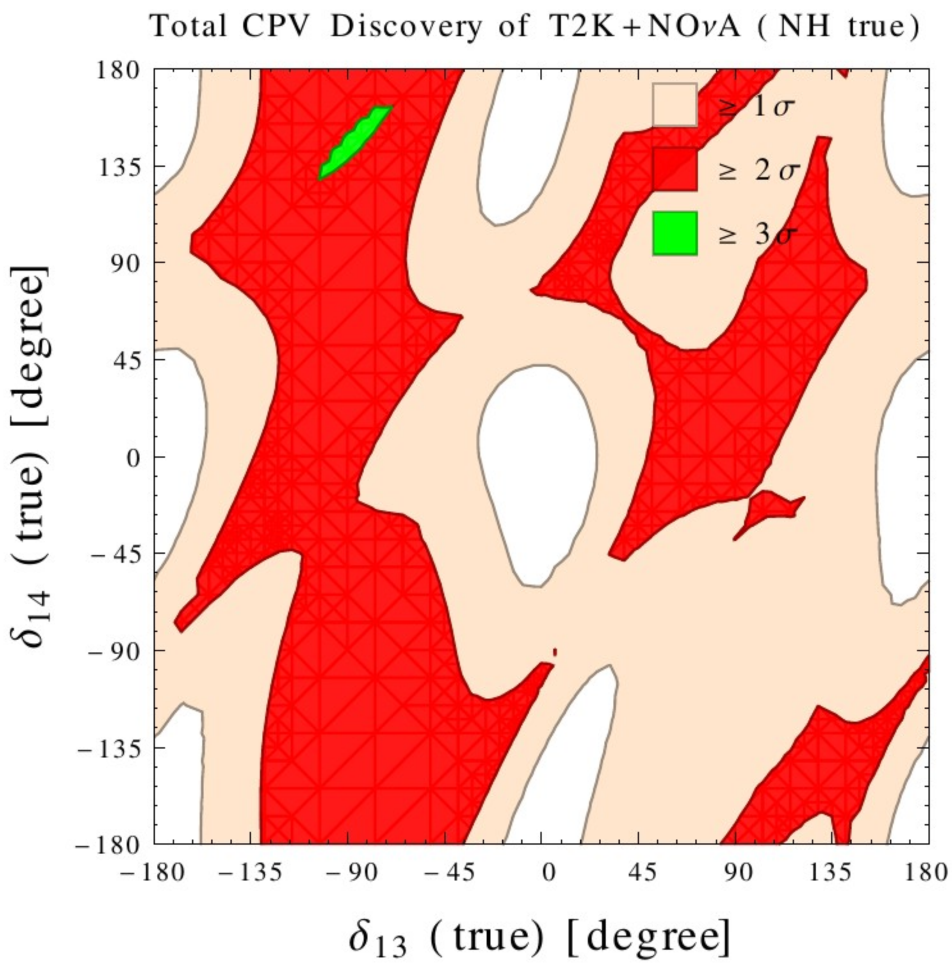


- Combining T2K & NovA result improves the potential of CPV discovery than considering each at one time.

- CPV discovery gets substantially deteriorated w.r.t 3-flavor in presence of a sterile neutrino depending on the new CP phase associated with 1-4 mixing.

- CPV induced by only δ_{14} is always below 2σ
So we do not show this.

Total CPV !

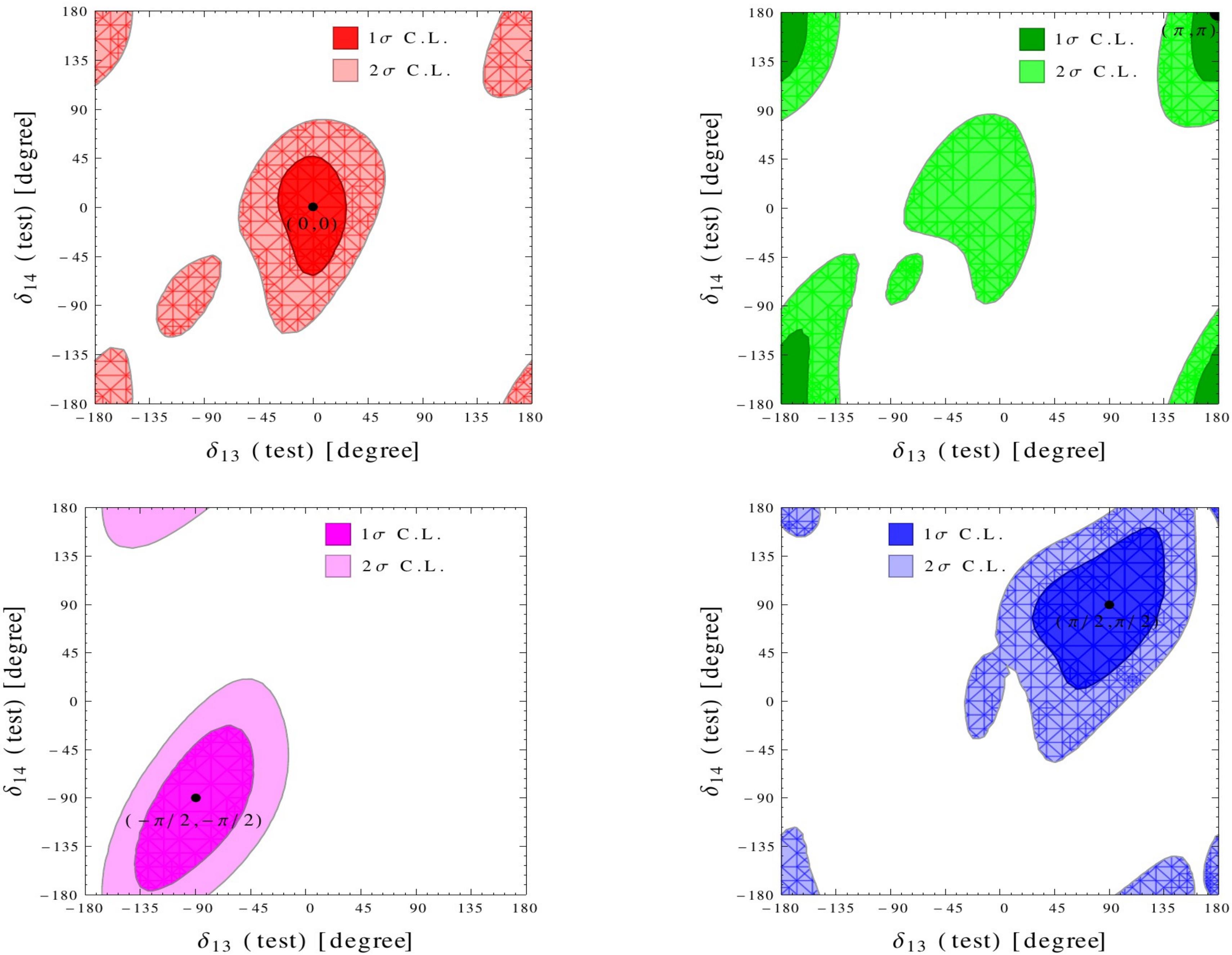


This is the CP–violation induced by **$\sin\delta_{13}$ & $\sin\delta_{14}$** simultaneously.

For some combinations there is 3σ level ''total CPV'' discovery!

Reconstruction of CP phases

NH true



- CP reconstructing capability gives the complementary information to the CP-violation discovery potential.

- This information tells us how precisely we can measure the CP phases in an experiment independent of the amount of CP-violation (if present).

- The typical 1σ level uncertainty on the reconstructed phases is approximately 40^0 for δ_{13} And 50^0 for δ_{14}

- We see that at 1σ level, we can reconstruct a unique region in all cases.

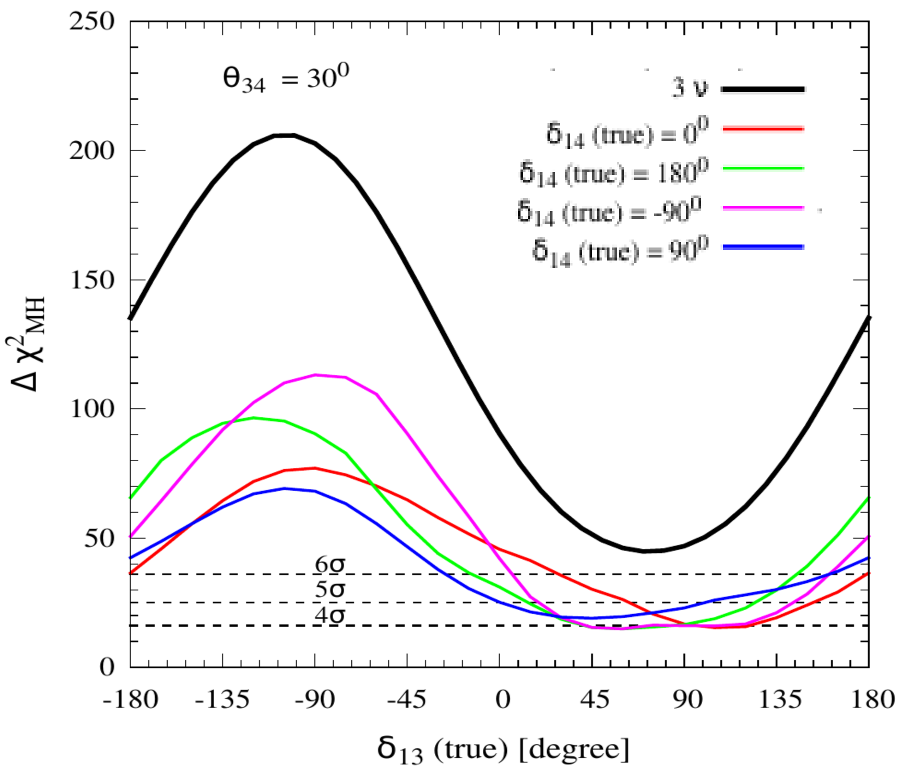
- But at 2σ level only $[-\pi/2, \pi/2]$ case gives the unique reconstructed region. In other cases spurious islands start to appear due to the wrong choice of hierarchy.

Prior knowledge of MH is very imortant !

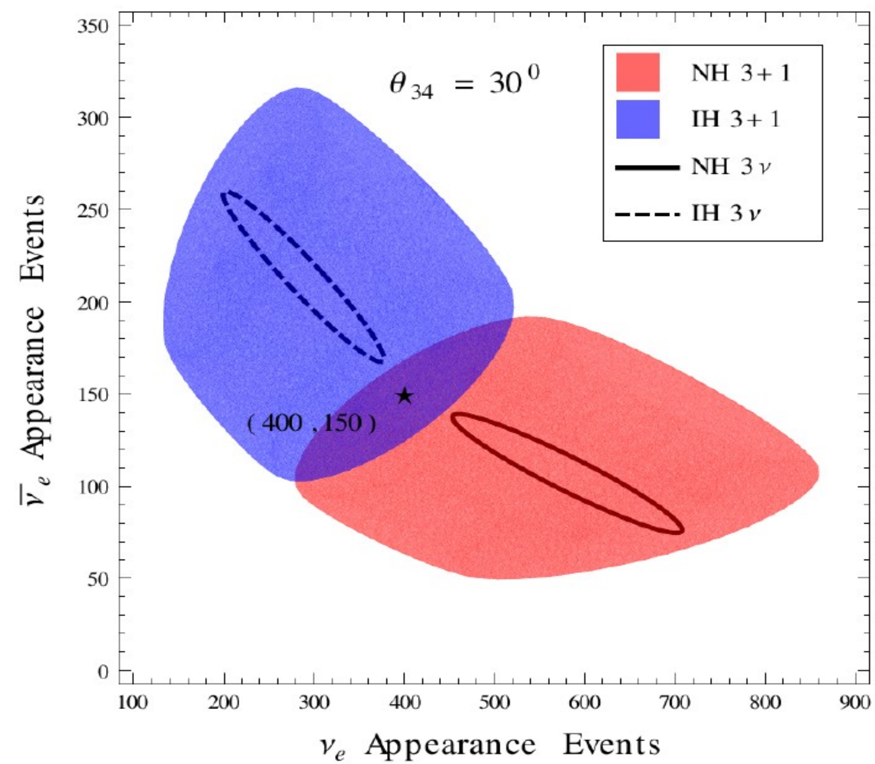
Part II : Some Results from DUNE

We are using 248 kt. MW. yr. of total exposure

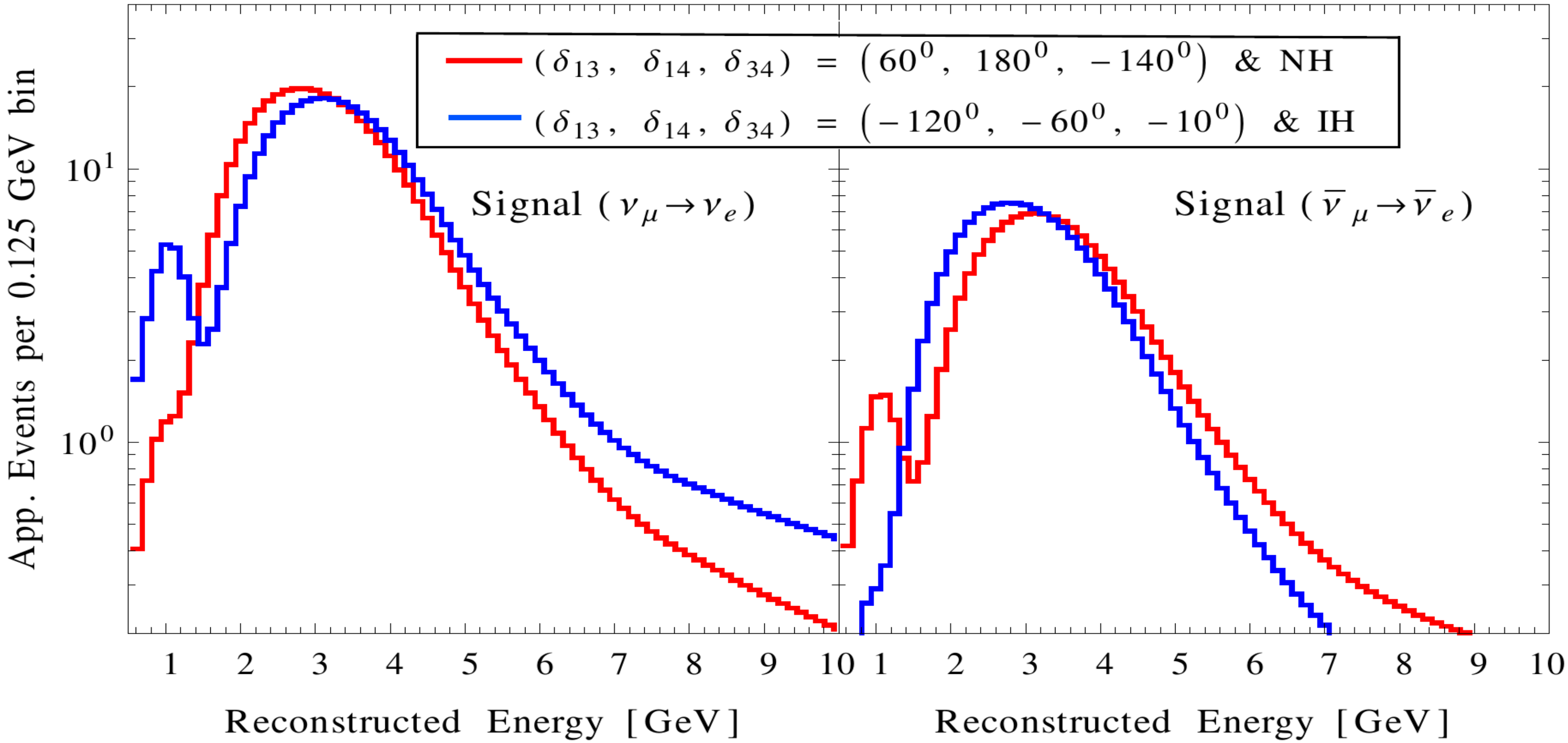
MH Discovery potential (NH true)



Bi-events convoluted plot



MH can drop down to below 4σ for large value of θ_{34} due to the degeneracy between three CP phases δ_{13}, δ_{14} & δ_{34}

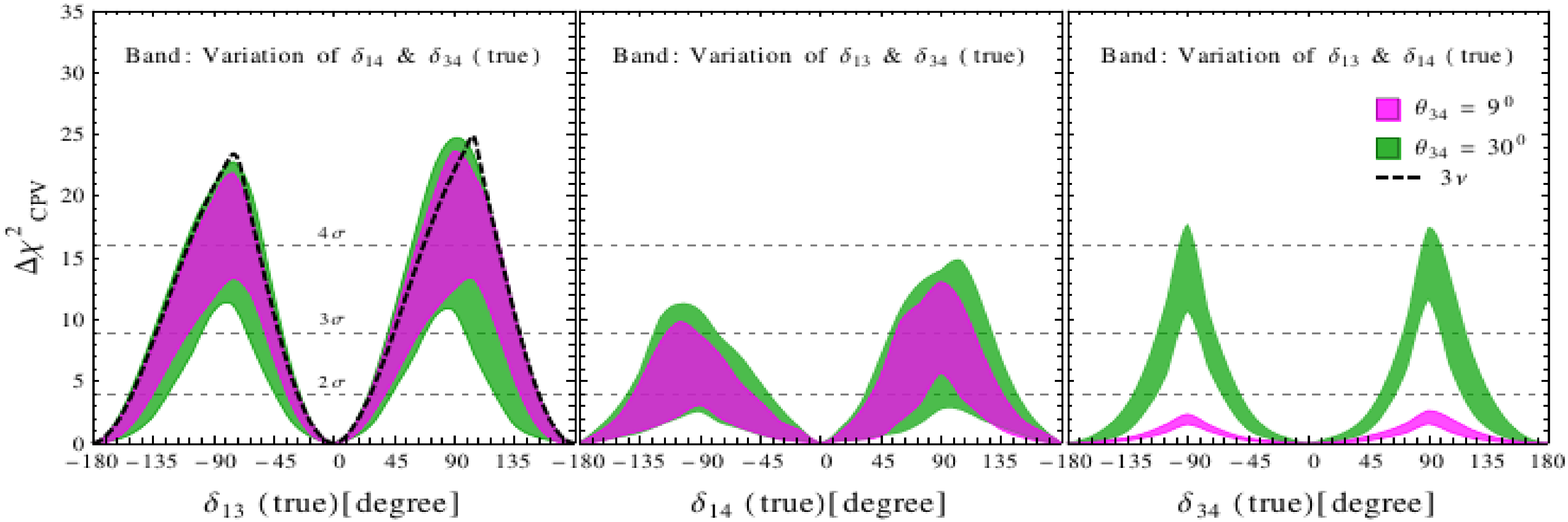


Overlap region between NH & IH in the previous transparency (for example, indicated by a star), corresponds to the no sensitivity to MH determination if we consider total event rates.

But we get 4σ MH discovery due to spectral rate.

Precise knowledge on spectral information is very important !

CPV Discovery potential



	θ_{34}	$N\sigma_{min}$ $[\delta_{13}(\text{true}) = -90^0]$	CPV coverage (3σ)
3ν		4.5	50.0%
3+1	0^0	3.9	43.2%
	9^0	3.4	32.0%
	30^0	3.3	16.0%

induced by δ_{13}

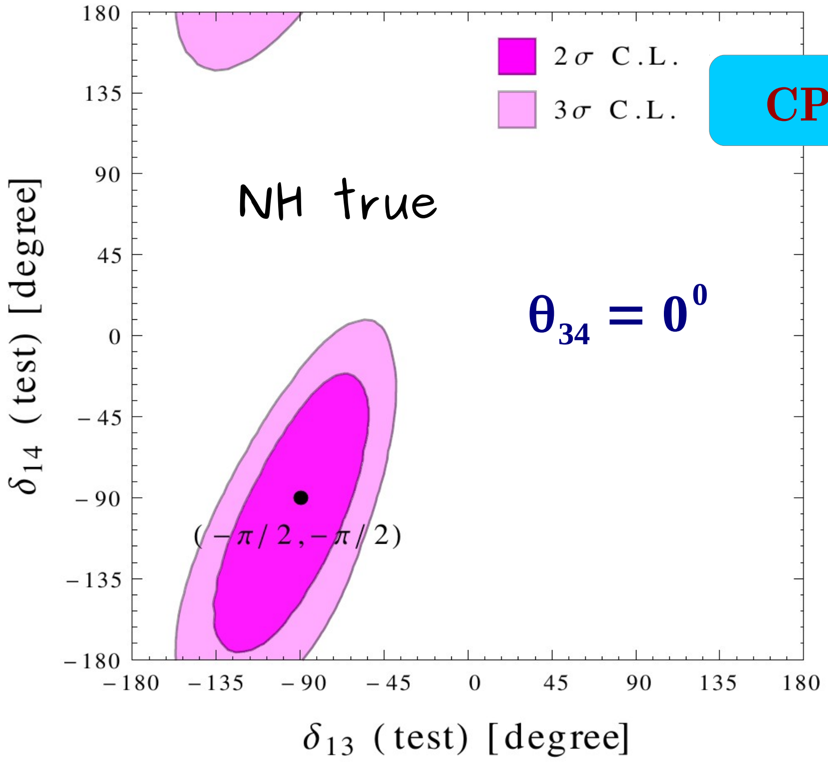
CPV coverage (3 σ) induced by δ_{13} corresponds to the lower border of the band corresponding to the different values of θ_{34}

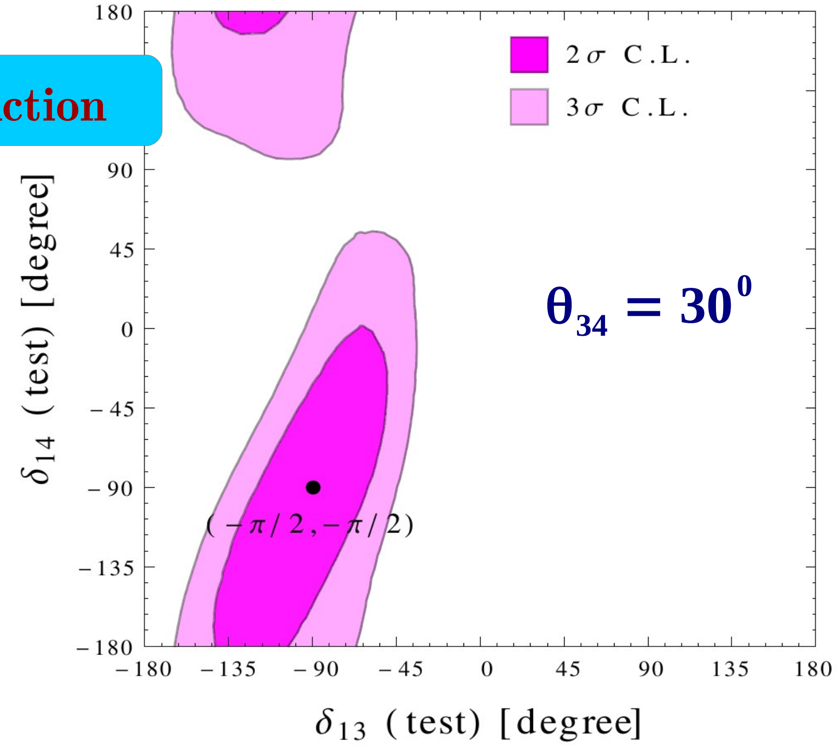
There is guaranteed 3σ level CPV discovery induced by δ_{13} for appreciable fraction of δ_{13} (true).

CPV induced by δ_{14} is not guaranteed at 3σ level.

If θ_{34} is large enough, DUNE can observe CPV induced by δ_{34}

CP Reconstruction





The typical 1σ uncertainty on the reconstructed CP phases is approximately $20^0 (30^0)$ for $\delta_{13} (\delta_{14})$ if $\theta_{34} = 0^0$. DUNE is much more effective than T2K & NovA in reconstructing the CP phases.

The reconstruction of δ_{14} (but not that of δ_{13}) appreciably degrades if θ_{34} is large.

Part III : Conclusion

- SBL experiments are not sensitive to the CP phases. We need LBL to explore the new phases. So, in the eventuality of a light sterile neutrino, the LBL setups would play a complementary role to the SBL experiments.

- MH gets substantially deteriorated with respect to the 3-flavor fit depending upon the phase associated with 1-4 mixing

- We have shown that the spectral information is very important for DUNE to get good sensitivity for MH determination.

- Prior knowledge of MH is very important to measure the CP phases precisely for T2K & NOvA

- We found that performance of (T2K, NovA & DUNE) in claiming the CPV discovery induced by δ_{13} gets substantially deteriorated in presence of a Sterile Neutrino

- The typical 1σ level uncertainty on the reconstructed phases in T2K + NovA is approximately 40^0 for δ_{13} and 50^0 for δ_{14}

- The typical 1σ uncertainty on the reconstructed CP phases is approximately $20^0(30^0)$ for $\delta_{13}(\delta_{14})$ if $\theta_{34} = 0^0$. DUNE is much more effective than T2K & NovA in reconstructing the CP phases.

- The reconstruction of δ_{14} (but not that of δ_{13}) appreciably degrades if θ_{34} is large.

- Prior knowledge of θ_{34} & it's associated phase δ_{34} is very important to measure the CP phases precisely for DUNE

- We hope that the analysis performed in these papers may give deep insight in exploring the new mass eigenstate.

Thank you !

Oscillation Probability in 3+1 in vacuum

$$P^{4\nu}_{\mu e} \simeq \left(1 - s^2_{14} - s^2_{24}\right) P^{3\nu}_{\mu e}$$

$$+ 4\, s_{14}\, s_{24}\, s_{13}\, s_{23} \sin\Delta\, \sin\left(\Delta + \delta_{13} - \delta_{14}\right)$$

$$- 4\, s_{14}\, s_{24}\, c_{23}\, s_{12}\, c_{12} \left(\alpha\Delta\right) \sin\delta_{14}$$

$$+ 2\, s^2_{14}\, s^2_{24}$$

In presence of matter

$$P^{4\nu}_{\mu e} \simeq \left(1 - s^2_{14} - s^2_{24}\right) \bar{P}^{3\nu}_{\mu e}$$

$$+ 2\, s_{14}\, s_{24}\, \Re\left(e^{-i\,\delta_{14}}\, \bar{S}_{ee} \bar{S}^*_{e\mu}\right)$$

$$+ s^2_{14}\, s^2_{24} \left(1 + \bar{P}^{3\nu}_{ee}\right)$$